Monolithic Millimeter-Wave Source Incorporating Planar Surface Wave Assisted Antenna

Kevin M. K. H. Leong, Vesna Radisic[1], Lorene Samoska[2], Yongxi Qian, and Tatsuo Itoh

Department of Electrical Engineering
University of California, Los Angeles, 405 Hilgard Ave., Los Angeles, CA 90095

[1]HRL Laboratories, LLC, Malibu, CA 90265

[2]Jet Propulsion Laboratory, Pasadena, CA 91109

***Abstract* - A monolithic 120 GHz free-space, continuous-wave source capable of providing 10 dBm of EIRP at 11.1% DC-to-EIRP conversion efficiency is presented. We utilize both the excellent high frequency performance of InP based HEMT technology developed by HRL along with the newly developed surface wave assisted antenna concept. Because the antenna itself needs to be fabricated on a high dielectric constant substrate, monolithic integration with MMIC circuits becomes straightforward**

I. Introduction

Millimeter-wave systems have appealing features for an extensive range of applications. One of the main driving forces for their attraction is the interaction between the atmosphere and electromagnetic waves at these frequencies. Long-range systems such as automotive radar and radio astronomy take advantage of the atmospheric propagation windows, which occur at 77, 94, 140, and 200 GHz. In addition, use of millimeter-waves for space-to-space data links has also become very alluring; because of the need for high-speed data transfer, requiring large bandwidths.

The advancement of such high frequency systems greatly relies heavily on the availability of high power sources. Although, vacuum tube based electronics are known to be the dominant technology for power generation in the millimeter wave region, solid-state electronics are more desirable in terms of size, weight, and manufacturability. However, with current device technology, power produced by a single solid-state device is often not enough to meet the system requirements. Therefore, the power of several devices is often times combined, either by using waveguides or using free-space power combining techniques [1-3]. Inherently, the overall source efficiency depends on both the active devices as well as the passive circuit combiner, namely the radiating antenna or waveguide transition.

This paper addresses both concerns. First the oscillator needs to provide significant power at good RF-DC efficiency. Our approach utilizes HRL InP HEMT technology with maximum frequency of oscillation (f_{max}) of 600 GHz and extrinsic cutoff frequency (f_τ) of 180 GHz. Second, we address the fundamental problem of surface wave generation in high dielectric constant materials such as InP. Enormous effort has been spent in developing techniques to eliminate generation of surface waves, which leads to undesired power leakage, as well as antenna performance degradation. In many cases, these solutions require complex machining of the circuit substrate or the addition of separate substrates, making compatibility with standard MMIC process very difficult [4-5]. In complete contrast, we propose an antenna that makes use of the generation of surface waves, resulting in a highly efficient, fully MMIC compatible, broadband radiator, which may also be used as a transition from planar circuit to waveguide [6-7]. This approach offers complete monolithic integration of circuit and antenna on a single substrate without sacrificing efficiency, and is accomplished by simply using standard processing techniques.

II. Oscillator Design And Measurement

Fig. 1 shows the photograph of the fabricated oscillator circuit. It consists of a 4×37 μm gate periphery HEMT device in a common source configuration. The series feedback element is a grounded CPW transmission line at the source. The bias point of the oscillator is chosen to maximize the output power. Therefore the HEMT is biased for Class A operation. The input and output matching are chosen to provide maximum output power and to satisfy the oscillation condition.

Frequency of oscillation was measured by mixing the oscillator output with a Millitech 90 GHz Gunn oscillator. The mixer output is connected to an 8564E spectrum analyzer. Fig. 2 shows the oscillation spectrum for the circuit is biased at the drain voltage of 2.5 V, gate voltage of –0.036 V, and the drain current of 25 mA. The oscillation frequency for this bias condition is 119.8 GHz. The phase noise is 93 dBc/Hz at 1 MHz offset. The oscillation spectrum and phase noise result can be further improved if the oscillator is biased through a battery, rather than a power supply.

The output power is measured using WR-8 power sensor and power meter, which are directly connected to the oscillator output. The best output power is obtained at drain bias of 2.5 V, gate voltage of 0 V, and drain current of 36 mA. The measured output power is 8.7 dBm or 7.4mW. The RF to DC efficiency of the oscillator is 8.2 %.

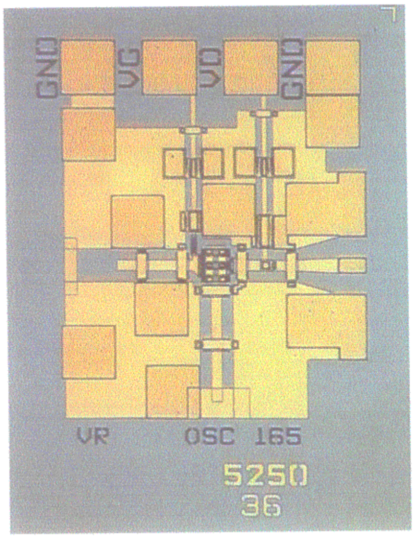

Fig. 1. Photograph of the fabricated oscillator.

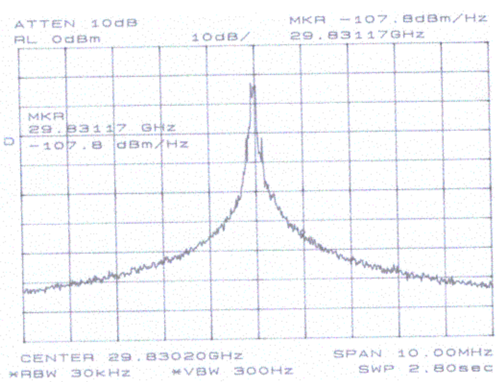

Fig. 2. Measured oscillation spectrum.

III. Planar Surface Wave Assisted Antenna

The proposed planar surface wave assisted antenna has recently appeared in literature under the name 'quasi-Yagi antenna,' [8] because of its similarity in configuration with the classic Yagi-Uda dipole array antenna. Further study indicates that the antenna actually relies on the generation of TE_0 surface-wave as its primary source of free-space radiation. For this reason the antenna is best suited for fabrication on materials with high dielectric constants, making it ideal for integration with MMIC which are fabricated on InP and GaAs substrates. Contrary to conventional printed dipole antennas, unidirectional, end-fire radiation is achieved by utilizing the grounded metal of the feed line as a TE_0 surface-wave reflecting element. Furthermore, radiation efficiency of greater than 92% was measured in the microstrip version of the antenna both at X and V-band. This technique was also previously demonstrated as a low loss waveguide transition.

Although, this antenna was first demonstrated by using microstrip feeding, we utilize CB-CPW feeding for compatibility with the oscillator circuit discussed in the first section. A photograph of the monolithically fabricated CB-CPW fed antenna is shown in Fig. 3. The hollow patch at the end of the CPW line acts as a wideband transition between CPW to coplanar strip (CPS) mode [9]. The patch represents a wideband open circuit, which forces the current to flow between the two conductors of the CPS lines, which are used to feed the driver dipole, which then acts as the surface-wave generator. The second dipole behaves as a parasitic director element, which directs radiation towards the endfire direction. Both the top and bottom ground planes of the CB-CPW transmission line are truncated to serve as a surface-wave reflecting element, resulting in unidirectional, end-fire radiation. This eliminates the need for any separate reflector elements. Vias were used to eliminate the effect of the parasitic parallel plate mode, which leads to undesirable power leakage.

The CB-CPW fed antenna was first developed at X-band (8-12 GHz) [10] frequencies using an in-house FDTD code on 0.635 mm, Duroid, $\varepsilon_r = 10.2$. In order to obtain a first-order approximation of the F-band (90-140 GHz) design, a linearly scaled version of the X-band antenna was used. FDTD was again used to re-optimize the antenna on 50 μm, InP substrate, with estimated $\varepsilon_r = 12.6$, while neglecting metal loss.

Monolithic fabrication of the antenna was done using the same MMIC process used to fabricate the oscillator circuit. Although, special attention was given to the precise removal of the backside metallization, it simply required refinement of an already standard part of the fabrication process, which is used to make dicing of the circuit wafer easier. Note that for measurement and demonstration purposes only, the antenna and oscillator are connected through wire bonding. Complete monolithic integration of the components is easily realized.

On wafer probe measurements from 90 to 140 GHz were performed to determine the antenna's return loss. Special considerations were taken to ensure that the dipole portion of the antenna was not placed directly above any metal plane, including the probe station chuck. This would effectively short out the antenna, and not allow it to radiate. A 'dummy,' wafer was placed under the test wafer for added mechanical support and the antenna was allowed to hang off the edge of the metal chuck. Measurement indicates adequate 50 Ω impedance matching (S11 < −10 dB) for the entire band (fig. 4). We also observe improved matching at the center of the band, which corresponds with FDTD simulation.

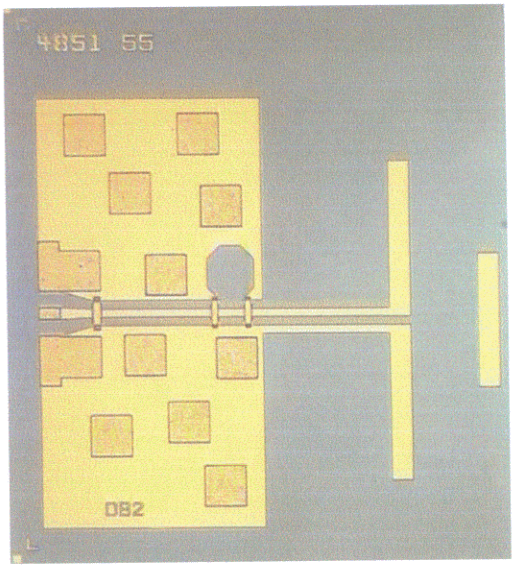

Fig. 3. Photograph of fabricated antenna.

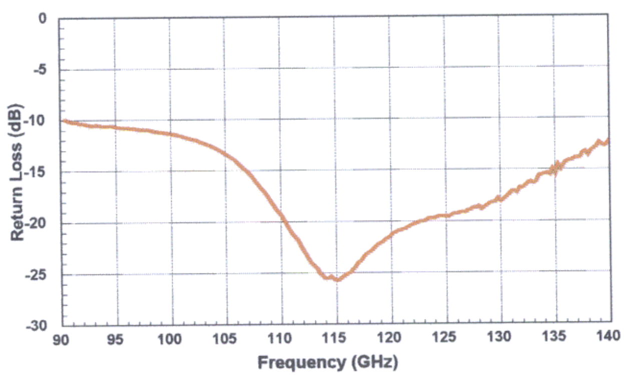

Fig. 4. Measured antenna return loss.

IV. 120 GHz CW Source

The combination of the two afore mentioned components, takes full advantage of the characteristics of both the millimeter-wave oscillator as well as the highly efficient planar antenna in realizing a fully monolithic, radiating active millimeter-wave source.

The two components were first diced, and then connected via wire bonds. Epoxy was used to mount the circuit onto a carrier with low dielectric permittivity ($\varepsilon_r \approx 1.1$). DC power was provided to the oscillator using a Picoprobe DC probe. Radiated power was measured at the source antenna's endfire direction using a WR-8 waveguide horn antenna and power meter. By de-embedding the receiving antenna gain, as well as the free-space loss we are able to deduce the source's effective isotropically radiated power (EIRP) to be 10 dBm. Isotropic conversion gain [11], which is the ratio between the EIRP and the DC power, was measured to be 11.1% at 120 GHz.

V. Conclusion

We have demonstrated a fully monolithic, MMIC compatible approach to free-space millimeter wave power generation. This is accomplished by using state of the art solid-state device technology in conjunction with newly developed surface-wave assisted antenna. Further improvement can be obtained by applying an integrated antenna approach in which the impedance of the antenna can be tailored for maximum power extraction from the device.

ACKNOWLEDGMENT

This work was funded by DARPA under contact number F33615-99-C-1512. The authors would like to thank Dr. Edgar Martinez of DARPA and Dr. David Chow of HRL Laboratories, LLC for guidance in this project.

The research described in this paper was carried out in part ~~by~~ at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] N.-S. Cheng, P. Jia, D. B. Rensch, R. A. York, "A 120-W X-band spatially combined solid-state amplifier." *IEEE Transactions on Microwave Theory and Tech.*, vol.47, (no.12), IEEE, pp.2557-61, Dec. 1999.

[2] R. Bashirullah, A. Mortazawi, "A slotted-waveguide power amplifier for spatial power-combining applications." *IEEE Transactions on Microwave Theory and Tech.*, vol.48, (no.7, pt.1), IEEE, pp.1142-7, July 2000.

[3] B. Deckman, D. S. Deakin Jr., E. Sovero, D. Rutledge, "A 5-watt, 37-GHz monolithic grid amplifier." *2000 IEEE MTT-S International Microwave Symposium Digest*, 2000. vol. 2, pp.805-808, June 2000.

[4] J. B. Muldavin, G. M. Rebeiz, "Millimeter-wave tapered-slot antennas on synthesized low permittivity substrates." *IEEE Transactions on Antennas and Propagation*, vol.47, (no.8), IEEE, pp. 1276-80, Aug. 1999.

[5] G. P. Gauthier, J.-P. Raskin, L. P. Katehi, G. M. Rebeiz, "A 94-GHz aperture-coupled micromachined microstrip antenna." *IEEE Transactions on Antennas and Propagation*, vol.47, (no.12), IEEE, pp.1761-6, Dec. 1999.

[6] N. Kaneda, Y. Qian, T. Itoh, "A broadband CPW-to-waveguide transition using quasi-Yagi antenna." *2000 IEEE MTT-S International Microwave Symposium Digest*, vol. 2. pp.617-20, June 2000.

[7] N. Kaneda, Y. Qian, T. Itoh, "A broad-band microstrip-to-waveguide transition using quasi-Yagi antenna." *IEEE Transactions on Microwave Theory and Tech.*, vol.47, (no.12), pp.2562-7, Dec. 1999.

[8] W. R. Deal, N. Kaneda, J. Sor, Y. Qian, T. Itoh, "A new quasi-Yagi antenna for planar active antenna arrays." *IEEE Transactions on Microwave Theory and Tech.*, vol.48, (no.6), pp. 910-18, June 2000.

[9] T. Q. Ho and S. M. Hart, "A Broad-Band Coplanar Waveguide To Slotline Transition,"*IEEE Microwave and Guided Wave Letters*, vol. 2, pp. 415-416, Oct. 1992.

[10] K. M. K. H. Leong, Y. Qian, T. Itoh, "First Demonstration of a Conductor Backed Coplanar Waveguide Fed Quasi-Yagi Antenna, "*2000 IEEE AP-S Int. Sym. Digest*, vol. 3, pp. 1432-35, July 2000.

[11] K. D. Stephan and T. Itoh, "A planar quasi-optical subharmonically pumped mixer characterized by isotropic conversion loss," *IEEE Trans. Microwave Theory and Tech.*, vol. 32, pp. 97-102, Jan. 1984.